Adaptation of rammed earth to modern construction systems: comparative study of thermal behavior under summer conditions

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Abstract

Buildings should be understood as a process that consumes energy in all their phases (design, construction, use and end-of-life) and, more specifically, the building envelope is clearly involved in all of them. For this reason, the International Energy Agency defines in its latest publication the improvement of building envelopes as one of the key points to reduce the energy consumption in buildings. In the present study, two sustainable construction systems based on rammed earth walls are adapted to modern requirements to be thermally tested and compared against three Mediterranean conventional systems under summer conditions. The experimentation was done by performing several experiments in free floating and controlled temperature conditions at real scale in five cubicle-shape buildings with inner dimensions 2.4 x 2.4 x 2.4 m. The purpose of this study is to demonstrate that more sustainable construction systems can be used instead of conventional ones, with higher embodied energy, and achieve similar thermal response. Results show that the reduction of rammed earth wall thickness strongly penalizes its thermal behavior. However, similar thermal response than conventional systems is reached when 6 cm of wooden insulation panels are added in the outer face of the cubicle-shape building.

Keywords

Sustainable building, embodied energy, thermal performance, rammed earth, wooden insulation

1. Introduction

The improvement of building envelopes has been identified by the IEA (International Energy Agency) as one of the key points to reduce the energy consumption in buildings [1]. The building sector was responsible for 19% of total greenhouse gases (GHG) emissions in 2010 [2] and one of the most energy consumer sub-sectors accounting around 32% of global final energy use [1]. Space heating and cooling represents 34% and 40% of energy consumption in residential and commercial buildings, respectively, and this consumption is directly related with the building envelope [3 - 7].

However, buildings must be considered as a process which consumes energy and affects the environment in all their phases (design, construction, use and end-of-life) and the building envelope is involved in all of them [8, 9]. Materials choice is a key element involved in design and construction phases, and the end-of-life of a building [10]. Reddy (2003) [11] demonstrated that embodied energy of buildings strongly depends on materials and building techniques choice by comparing embodied energy between basic building materials and floor and roofing systems commonly used in India as well as the energy expenditure during transportation. Authors concluded that embodied energy of materials can be reduced up to 62% when a proper selection of materials and systems is done. Similar results were obtained in Reddy (2009) [12], where the author demonstrated that 50% of embodied energy can be achieved by using alternative low-energy building technologies in walls, floor and roofing systems.

Within this context of sustainable materials for building design, earth is an ancient material that has been used in buildings until nowadays and its recovery as building material becomes more attractive when other parameters are taken into account as its low embodied energy, low price, availability and recyclability. As an example, Melià (2014) [13] compared the environmental impact of earthen plasters based on clay with conventional plasters based on cement or hydraulic lime using LCA methodology evaluated from a cradle-to-gate perspective. They demonstrated that total embodied energy in plasters can be halved by choosing earthen plasters instead of hydraulic lime and cement based ones.

Earth buildings and, in particular, rammed earth buildings provides suitable thermal resistance properties into walls using large thicknesses [14] and high thermal inertia due to its high mass [15]. Li et al. (2012) [16] experimentally demonstrated that thick rammed earth buildings (between 0.7 - 1.7 m) consumes less energy than normal rural buildings in different Chinese rural zones. However, construction systems used today tend to reduce thickness and mass of walls and rammed earth cannot provide a proper thermal behaviour when thin walls are used [17].

For this reason, the main aim of the present study is to experimentally demonstrate that similar thermal behaviour than in other conventional construction systems with high embodied energy can be achieved by using only low embodied energy construction materials and systems. To reach this goal, five house-like cubicles are thermally tested at real scale under summer conditions. Two of them were identically built with thin rammed earth walls and wooden green roof, the only difference between them is that one cubicle has non-insulated walls and, the other one has wooden insulation panels placed in the outer surface of walls and a finishing coating composed by clay and straw fibres. The other three were built using Mediterranean conventional construction systems, one of them without insulation. Furthermore, the experimental measurements presented in the paper provide unique available information to the scientific community to test technologies and provide data for validation of numerical models.

2. Experimental set-up

Five cubicles with different construction systems were studied in the experimental set-up of Puigverd de Lleida, Spain, (Figure 1) with Csa climate according to Geiger climate classification [18]. Two cubicles were built with rammed earth technique, an ancient and traditional construction system, and the other three were built with Mediterranean conventional construction systems. These three conventional construction systems used (among others) were previously tested and evaluated in Cabeza et al. 2010 [19]. All of them have the same inner dimensions (2.4 x 2.4 x 2.4 m) and orientation (N-S, 0º), with an insulated metal door in the north wall and no windows.

Figure 1. Puigverd de Lleida experimental set-up

As is well known, rammed earth was traditionally used with large thicknesses (from 50 cm to 1 m approximately) that provides good thermal and acoustic properties to buildings [15]. However, as mentioned before modern construction systems tend to use thinner walls than traditional ones with similar or better thermal responses [20, 21]. For this reason, rammed earth should be insulated if thin walls are used in order to achieve a good thermal response [**22**].

In the present study, rammed earth is adapted to modern construction systems by using thicknesses of 29 cm and by adding insulation. As a novelty, rammed earth was insulated in the outer face and a sustainable and low embodied energy insulation material was selected. This natural insulation material based on wooden fibres by-product does not adversely affect the embodied energy of the whole system. Furthermore, and following the same sustainable guidelines, a wooden green roof was selected as roofing system.

Each construction system is listed below and Figure 2 illustrates their constructive details:

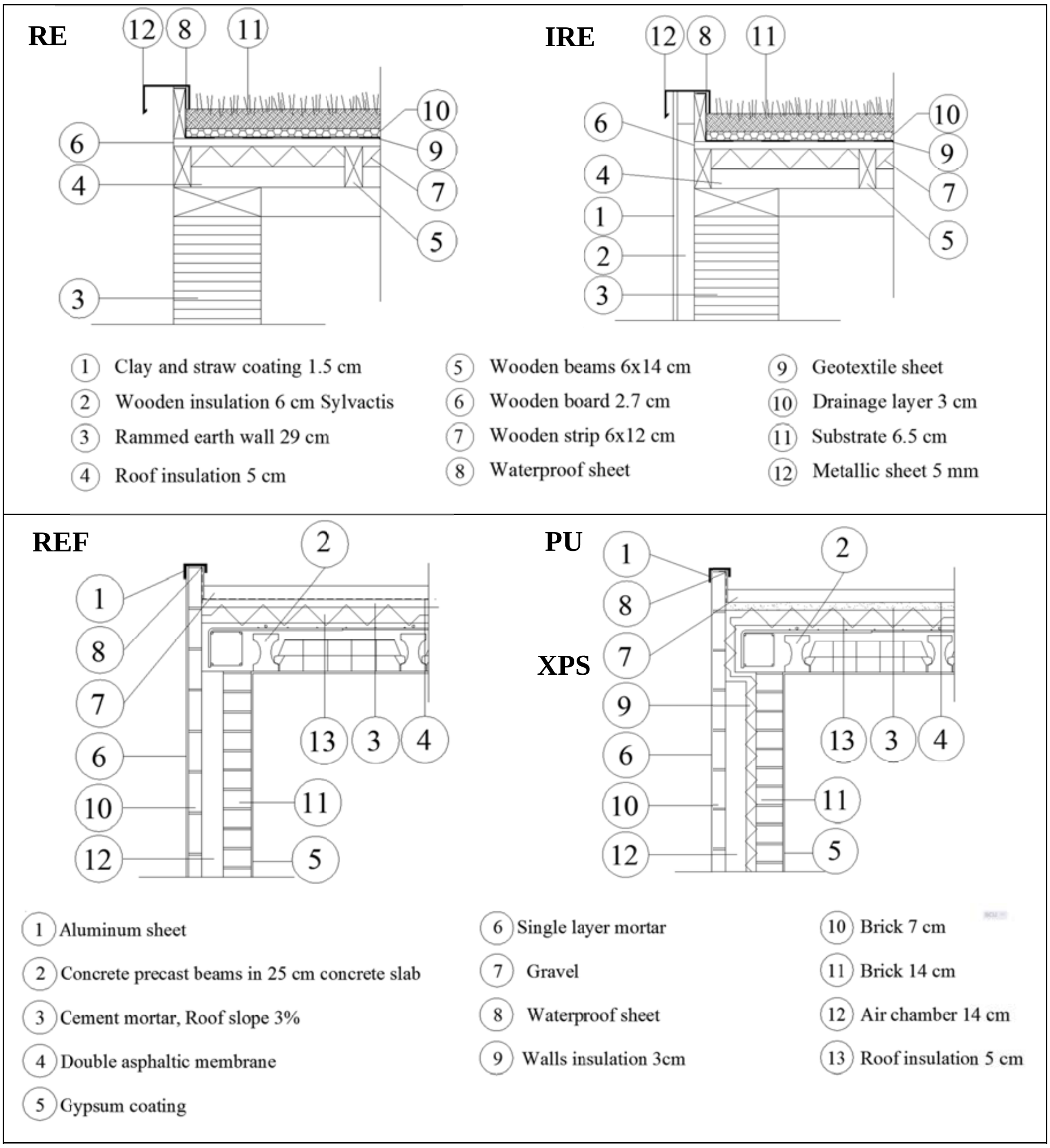

Figure 2. Construction systems details

1. Non-insulated rammed earth (RE): Load-bearing rammed earth walls of 29 cm (with ground humidity protection of 19 cm composed by one row of alveolar brick and a polypropylene waterproof sheet).

2. Insulated rammed earth (IRE): Same construction system than RE but walls are insulated with natural wood fibres panels of 6 cm (SYLVACTIS 140 SD ITE) and 1 cm of natural coating based on clay and straw (thickness < 2 cm).
3. Reference cubicle (REF): Gypsum, perforated bricks, air chamber, hollow bricks, and cement mortar coating. Structure made of 4 reinforced concrete pillars.
4. Polyurethane cubicle (PU): Same layer distribution than REF but with 3 cm of polyurethane sprayed foam between the perforated bricks and the air chamber.
5. Polystyrene cubicle (XPS): Same layer distribution than REF but with 3 cm of extruded polystyrene.

All foundations consist of a 3.60 x 3.60 m reinforced concrete base with gravel drainage layer and all roofs are insulated with 5 cm of polyurethane. Values of thermal conductivity of insulation materials used in walls are provided by each manufacturer as Table 1 specifies.

Table 1. Thermal conductivity of insulation materials used

	Thickness [cm]	Thermal conductivity [W/m·K]
Wooden panels	6	0.044
Polyurethane	5	0.028
Extruded polystyrene	5	0.034

Thermal transmittance in steady state, also known as U-value, was calculated as the inverse of the envelope thermal resistance [23]. Moreover thermal lag of walls were calculated according to the methodology presented in ISO 13786:2001 [24]. Table 2 presents the results of these calculations showing that thermal transmittance of the envelopes are significantly reduced when adding an insulating layer, being this reduction around 77% in case of rammed earth, and around 70% in case of typical brick constructive system. Moreover, the results also demonstrate that the addition of insulation also increases the thermal lag in all cases, and that the constructive system based on rammed earth presents higher thermal lag than the system based on bricks.

Table 2. Theoretical thermal transmittance and thermal lag of walls

	U [W/m^2·K]	Thermal lag [h]
RE	2.429	8.56
IRE	0.563	10.99
REF	1.210	6.87
PU	0.383	8.32
XPS	0.435	8.31

Cubicles are fully monitored to register inner temperature and humidity (using ELEKTRONIK EE21 at a height of 1.5 m with an accuracy of ±2 %) and surface wall temperatures (using calibrated Pt-100 DIN B sensors with error ±0.3 ºC which measure east, west, north and south inner surface wall temperatures). Furthermore, temperatures inside walls (north, south, east and west) as well as temperatures between layers (coating – insulation – rammed earth wall) in RE and IRE are also measured to show the temperature profile of insulated and non-insulated rammed earth cubicles. Figure 3 shows the location of all the sensors mentioned above in IRE cubicle.

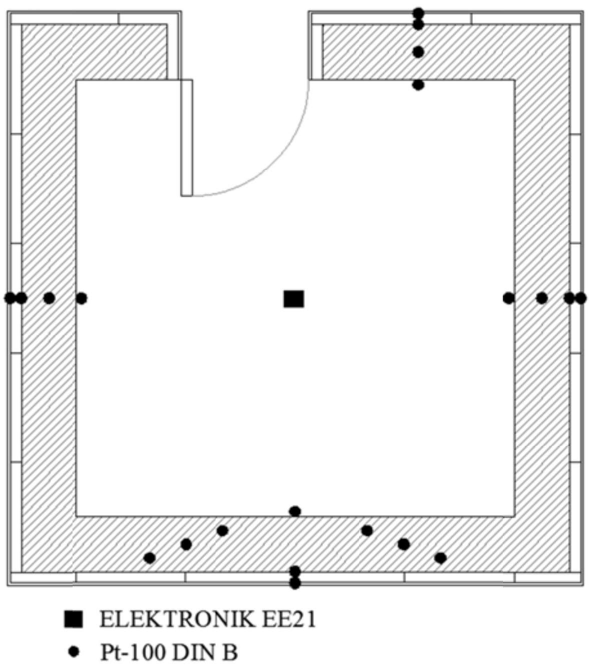

Figure 3. Location of sensors in IRE cubicle (floor plan)

Each cubicle has a domestic heat pump (Fujitsu Inverter ASHA07LCC) to cover cooling demand and its consumed electrical energy (from now called energy consumption) is measured by an electricity meter.

The experimentation was carried out during summer 2015 and two different tests were driven:

- Free floating: Heat pump is not used during this experiment in order to compare the evolution of cubicles inner temperatures.
- Controlled temperature: Heat pumps were programmed to perform under three different demand situations: two within common comfort range (21ºC and 24ºC) and one with high cooling requirements (18ºC). In addition, energy consumptions were measured and compared.

3. Results and discussion

As it has been mentioned in the previous section, experiments were carried out during summer 2015 where significant testing periods for each experiment were selected in order to evaluate the performance of the different construction systems. It is important to remark that transitory periods between experiments are not analysed until get inner temperatures of cubicles stable.

Climatic data registered as average temperatures (maximum and minimum), thermal amplitude, average humidity (maximum and minimum), average maximum solar radiation, and average solar radiation of the selected weeks are listed in Table 2.

Table 2. Climatological data in the selected weeks (2015)

		Selected weeks data				
		5th-11st June SP-18ºC	**18th-24th June SP-21ºC**	**11st-17th August SP-24ºC**	**10th-13th September FF cloudy**	**19th -22nd September FF sunny**
T	[ºC]	22.7	24	23.9	20.9	16.6
T_{max}	[ºC]	34.1	33.1	31.9	28.9	27.8
T_{min}	[ºC]	12.3	15.2	16.1	15.4	6.5
Thermal amplitude	[ºC]	21.8	17.9	15.8	13.5	21.3
H	[%]	58	57	63	78.9	67.2
H_{max}	[%]	93	86	91	98.4	97.3
H_{min}	[%]	25	29	35	49.1	30.2
Rad_{max}	[W/m^2]	1,164	1,107	1,123	1,035	904
Rad/day	[kWh/m^2 ·day]	92	105	86	50	75

As it can be observed, temperature, humidity and radiation data are different in each selected week. Nevertheless, since the methodology follows a comparative analysis, the experimental results would be used to evaluate the energy performance of rammed earth cubicles in comparison to conventional construction systems under the different analysed weather conditions.

Free floating conditions

Indoor temperature of each cubicle is evaluated under two different conditions: a) cloudy days (from September 10th to 13th) and sunny days (from September 19th to 22nd) as Figure 4 shows.

REF and RE cubicles have the largest indoor temperature oscillations, showing temperature differences during day-night period between 2-3 ºC and 1-2 ºC in RE and REF cubicle, respectively, in cloudy days. During sunny days, indoor temperature differences in RE and REF are bigger (3.5-4.3 ºC in RE and 2-2.6 ºC in REF), so that, they are notably sensible to outer conditions.

On the other hand, despite insulated cubicles (IRE, PU and XPS) have different construction systems in walls and roofs, they show similar indoor thermal temperature profiles with temperature differences between day and night periods around 0.5 ºC and 1.5ºC in both, cloudy and sunny days.

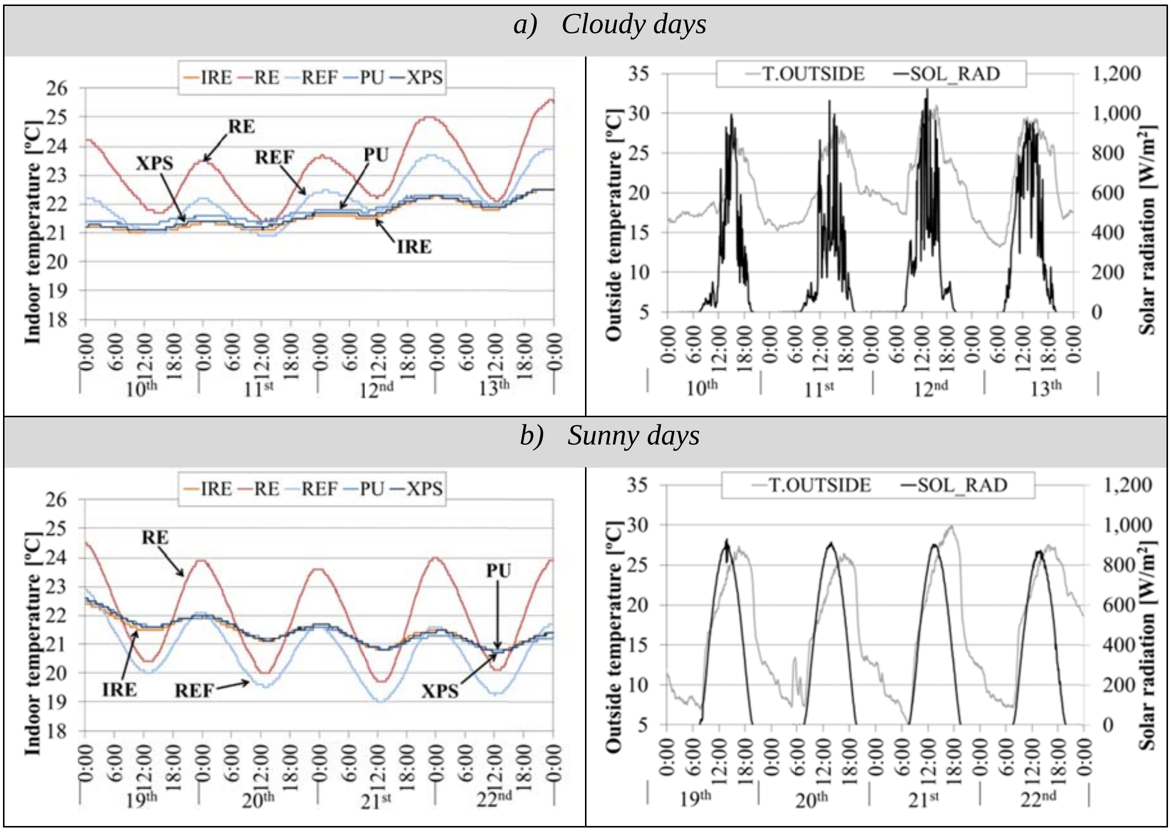

Figure 4. Inner temperature profiles of cubicles and ambient temperature of cloudy and sunny days. September 2015

Furthermore, two experimental dynamic parameters are also evaluated in each south wall in order to compare the dynamic response of each construction system:

- The thermal lag between outside and inner surface south wall temperature peaks in each cubicle.
- The thermal stability coefficient (TSC).

The evaluation was performed following the methodology used in [25] where outside and inner surface south wall temperature data is adjusted to a sinusoidal curve as:

$$Temp = a_0 + a_1 \cdot t + a_2 \cdot \sin(\omega_1 \cdot t + a_3) + a_4 \cdot \sin(\omega_2 \cdot t + a_5) + a_6 \cdot \sin(\omega_3 \cdot t + a_7) \quad (1)$$

where,

w_1, w_2, w_3	frequencies corresponding to periods of 24, 12, and 6 h, respectively
a_i	coefficients used to adjust the function

Figure 5 shows an example of data adjustment in one day following the methodology described above.

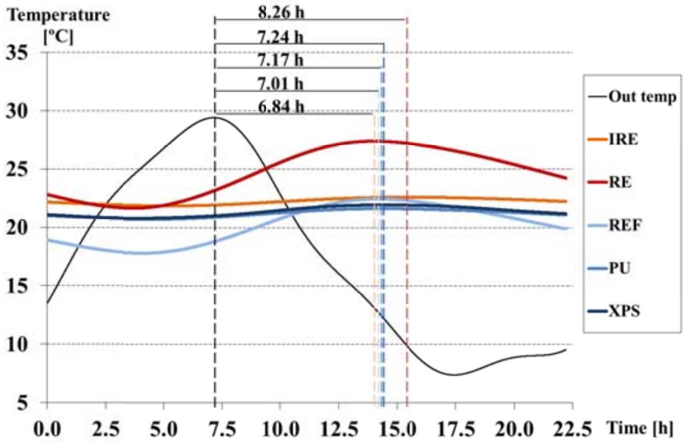

Figure 5. Thermal lag [h] between outside and inner surface south wall temperature peaks

Once experimental temperature profile data is adjusted to sinusoidal curves, maximum peak temperatures between outside and south walls in each cubicle can be calculated in order to see thermal lag provided by each construction system. On the other hand, TSC can be calculated as the ratio between outside thermal amplitude (maximum and minimum temperature achieved) and south wall thermal amplitude, separately, for each cubicle. In order to maximize the adjustment of equations to real experimental data, each day was evaluated separately due to temperature profiles were different depending on the day (see Figure 4).

Figure 5 shows the evaluation of thermal lag for one specific day; however, in order to provide a more robust lecture of the experimental measurements, the average of results and the standard deviation are calculated for sunny and cloudy days as Figure 6 shows.

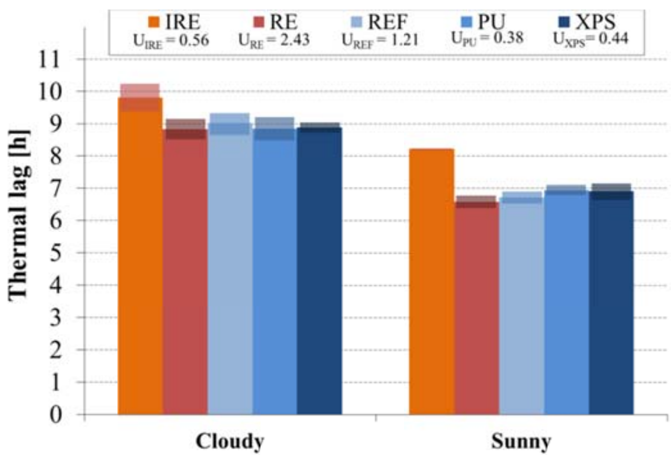

Figure 6. Average thermal lag [h] in sunny and cloudy days

In both climatic conditions IRE south wall shows the largest thermal lag, even having higher thermal transmittance than PU and XPS walls, around 1 h longer in cloudy days and 1.2 h in sunny days. Experimental results show that the use of insulation in the rammed earth constructive system provides a significant increase in the thermal lag, while no effect was observed in case of conventional Mediterranean construction (REF, PU and XPS). Taking into account TSC results (Table 3) IRE cubicle also has the best thermal stability if results are compared against PU and XPS, which are 26% and 34% higher than IRE, respectively, in cloudy days; and 30% and 66%, in sunny days. On the other hand, as expected, high TSC are obtained in RE and REF cubicles being even higher in RE cubicle.

Table 3. TSC for each cubicle in cloudy and sunny days

	IRE	**RE**	**REF**	**PU**	**XPS**
Average Cloudy	0.059	0.191	0.125	0.074	0.079
Std. dev.	0.015	0.058	0.037	0.026	0.026
Average Sunny	0.030	0.256	0.206	0.038	0.049
Std. dev.	0.004	0.007	0.006	0.003	0.003

Controlled temperature – set point 18ºC, 21ºC and 24ºC

In Figure 7, the daily energy consumption of the HVAC as well as the ambient temperature and solar radiation are shown for three weeks operating under different set points of indoor temperature: 18ºC, 21ºC and 24ºC.

The energy consumption of heat pumps has been evaluated from June 5th to 11st with set point 18 ºC (Figure 7 A). This week can be divided into two main parts taking into account ambient conditions and, as a consequence, energy consumption of cubicles. The first three days were completely sunny with 25 ºC of thermal amplitude and an average maximum solar radiation of 1000 W/m^2. Similar energy consumption was registered in insulated cubicles (around 3 kWh/day) and, as expected, non-insulated cubicles consume between 35-67% more than the insulated ones, and having RE cubicle the highest consumption (around 16% more than REF). Cloudy days can be noticed in the second part of the week with shorter thermal amplitude (15 ºC). In general, energy consumption in each cubicle is lower due to milder temperatures but trends of consumption are the same than in sunny days.

The second week under study (from June 18th to 24th) with controlled temperature of 21ºC (Figure 7 B) shows mostly sunny days with high temperatures during day and night periods that shortens the thermal gradient to 17.9 ºC. Once again, all insulated cubicles have approximately the same energy consumption, with slight differences in PU cubicle that consumes less energy than IRE and XPS. In this week, the energy consumption of insulated cubicles is reduced around 41% by increasing the set point 3 ºC even having higher outside temperatures. Energy consumption of non-insulated cubicles also decreases by increasing the set point but still remains high when compared against insulated cubicles. However, results are less visible (12% and 21% in IRE and REF, respectively) because non-insulated cubicles are more sensitive to ambient conditions and, therefore, high temperatures affect them heavily.

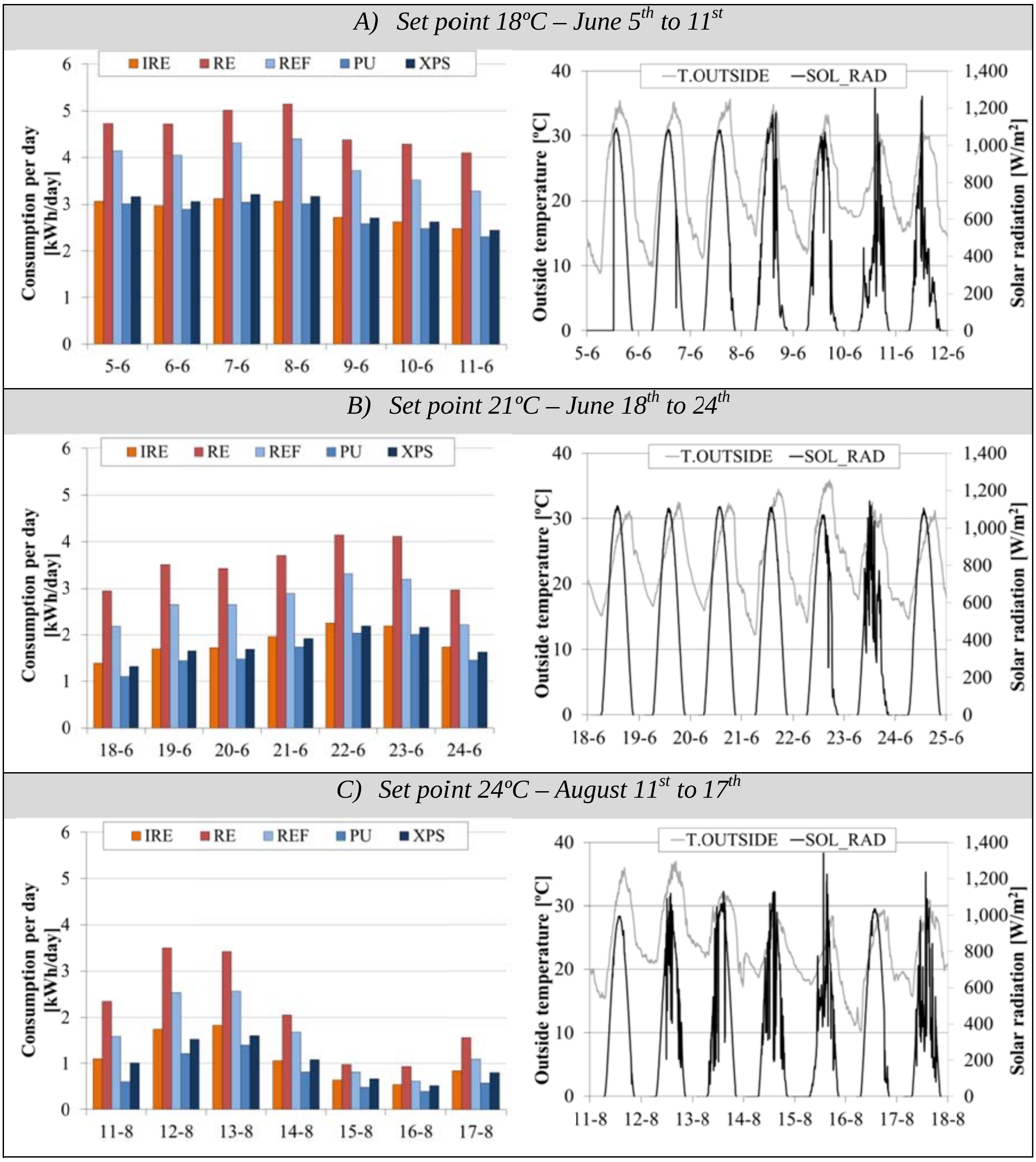

Figure 7. Daily energy consumption of heat pump [A) set point 18ºC, B) set point 21ºC and C) set point 24ºC], solar radiation and ambient temperature (2015)

Finally, the heat pump was set at 24 ºC (Figure 7 C) and energy consumption is evaluated in one selected week (from August 11st to 17th). In spite of having mostly cloudy days, the outside

temperature remains high during day and night periods (average thermal amplitude of 15.8 ºC). Results show the same trend than in previous experiments the first three days of the week: insulated cubicles consume approximately the same (IRE and XPS registered the same energy consumption while PU consumes slightly less energy) and non-insulated cubicles have high energy consumption, especially IRE cubicle. Then, outside temperature approaches the set point and, therefore, the energy consumption is reduced in all cubicles. However, it is important to remark the reduction of energy consumption, especially, in non-insulated cubicles.
Energy savings (Table 4) of 30% are achieved in IRE and XPS cubicles if results are compared with the reference, even though the set points are different. Otherwise, the PU cubicle increases its energy savings from 30% in set point 18 ºC to 40% and 50% using 21 ºC and 24 ºC, respectively.

It is important to remark that the lowest total energy consumption registered in one week is obtained by setting heat pumps at 24 ºC, according to results presented in Figure 7 and Table 4.

Table 4. Total energy consumption [kWh] and energy savings [%] in one week

Set Point [ºC]	**Energy [kWh] and savings [%]**	**IRE**	**RE**	**REF**	**PU**	**XPS**
18	[kWh]	20.06	32.52	27.52	19.38	20.45
	[%]	-27.1	+18.2	0.0	-29.6	-25.7
21	[kWh]	15.00	28.56	21.81	13.01	14.46
	[%]	-31.2	+30.9	0.0	-40.3	-33.7
24	[kWh]	8.34	15.77	11.54	5.91	7.70
	[%]	-27.7	+36.6	0.0	-48.8	-33.3

Wood panels' insulation effect

In this section the insulation effect of wood panels added to rammed earth is analysed during free floating and controlled temperature experiments in the south wall. Figure 8 (right) illustrates the surface temperatures evolution between layers as (1) inner surface wall temperature, (2) between the insulation, and the wall and (3) between the outer coating and the insulation (see Figure 3).

The plotted day was chosen according to the longest thermal gradient between coating-insulation and inner surface wall temperatures in the period under study. In order to compare and demonstrate the insulation effectiveness, the thermal profile of RE south wall is also illustrated in Figure 8 (left).

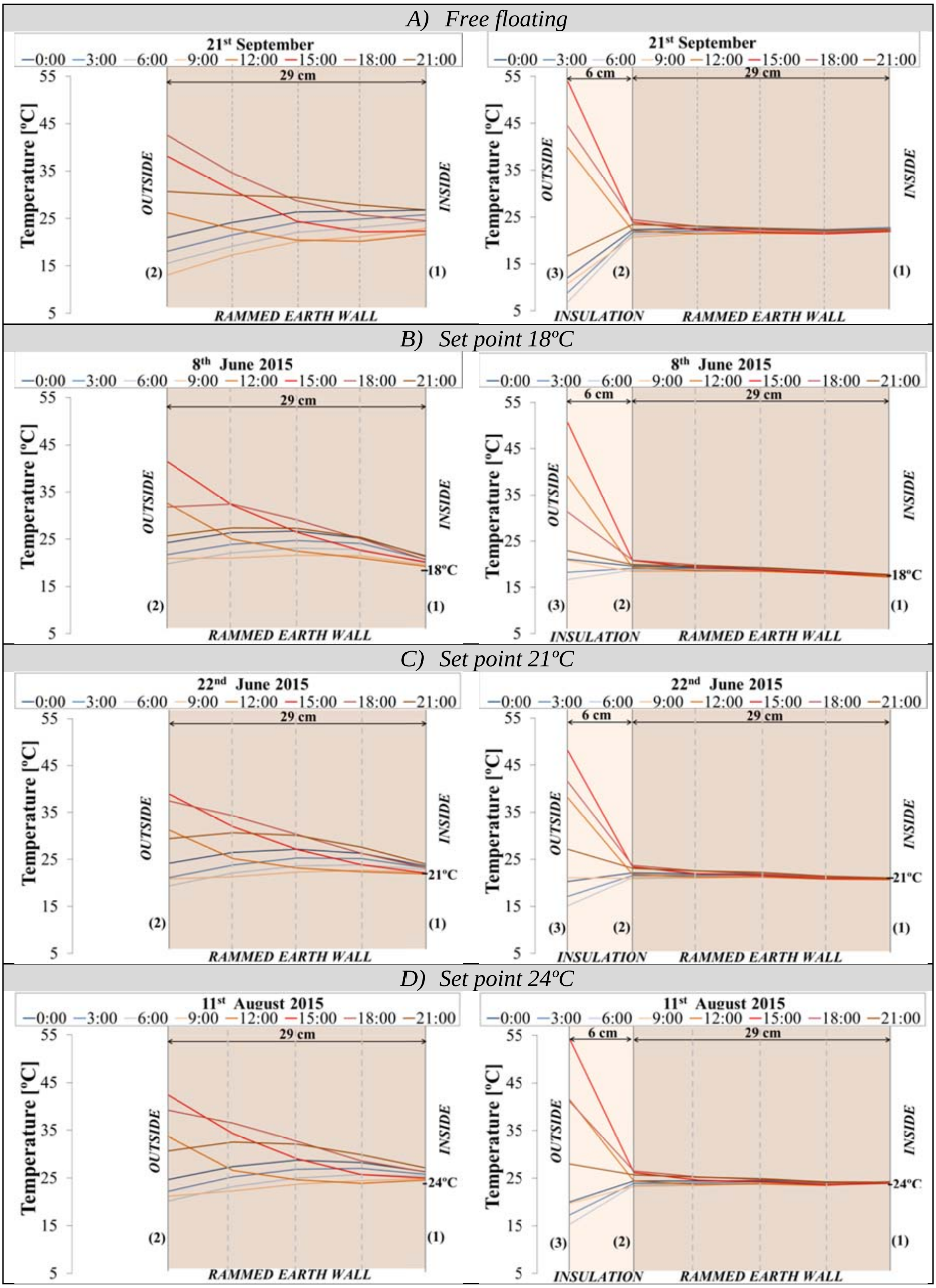

Figure 8. Thermal profile of IRE (right) and RE(left) south wall [A) free floating, B) set point 18ºC, C) set point 21ºC and D) set point 24ºC]

Temperature is mostly reduced by wood insulation panels as Figure 8 (right) demonstrates. In particular, wood insulation reduces up to 90.7% the temperature of the south wall at set point 18ºC whereas rammed earth only reduces 9.3%. Similar behaviours are observed at set point 21ºC and 24ºC, where wood insulation reduces 91.2% and 92.4%, respectively, the temperature of the south wall (Table 3).

On the other hand, temperature profiles of both south walls in free floating conditions (Figure 8 A) are consistent with the results provided in Figure 4, showing large temperature fluctuations in RE cubicle while in IRE cubicle remains almost constant.

It is also important to highlight that in the case of the non-insulated cubicle the rammed earth layer acts as a thermal buffer, storing heat during peak load hours and releasing it during night-time, while in the case of the cubicle with insulation, the high thermal mass of rammed earth is exposed to a weak thermal gradient and hence does not need to release during the night any stored heat. Moreover, temperature of set points are not reached in the inner surface of rammed earth wall, being always slightly higher and not constant, while in IRE south wall are perfectly reached.

Table 3. Wood panels' insulation and rammed earth thermal effect in IRE cubicle

		8th June 2015 Set point 18 ºC	**22nd June 2015 Set point 21 ºC**	**11st June 2015 Set point 24 ºC**
Maximum temperature between coating – insulation (3)	[ºC]	51.4	48.7	54.7
Maximum temperature between insulation – wall (2)	[ºC]	21.0	23.7	26.7
Maximum temperature of inner surface south wall (1)	[ºC]	17.9	21.3	24.4
Insulation effect	[%]	90.7	91.2	92.4
Rammed earth effect	[%]	9.3	8.8	7.6

4. Conclusions

Five cubicles with the same inner dimensions and orientation but different construction systems are thermally tested at real scale. Two of them were built with traditional construction systems (RE and IRE) and the other three with Mediterranean conventional construction systems (REF, PU, and XPS). Thermal responses of cubicles are evaluated under free floating and controlled temperature conditions.

First of all, when cubicles are tested in free floating conditions, results show that construction systems used in roofs and walls in RE cubicle are not able to achieve good thermal response, having worse results than in REF cubicle. It is important to remark that the reduction of rammed earth wall thickness is heavily penalizing its thermal behavior. Otherwise, when an external wooden insulation of 6 cm is added into rammed earth walls (IRE), its thermal response is improved notably achieving inner temperature profiles very close to PU and XPS under sunny and cloudy conditions. Despite IRE walls have higher thermal transmittance than PU and XPS, they have the best dynamic parameters with the longest thermal lag and the best TSC. As a result of a combination of dynamic and steady-state parameters, similar inner temperature profiles are obtained in all insulated cubicles.

Experimental results demonstrated that the addition of an insulating wood panel of 6 cm has a significant effect in the thermal performance of the whole building, showing a reduction of the electrical energy consumption of heat pumps around 45% when operating at different set points.

Wooden insulation panels reduce the temperature between outer and inner surface south wall 90.7% and 93.4%, meanwhile rammed earth only reduces between 7.6% and 9.3% in controlled temperature conditions. On the other hand, the effect of rammed earth is more visible when insulation material is not added because temperature differences between inner and outer surfaces are bigger.

Traditional materials as earth and wood, which are sustainable and environmentally friendly materials, can be adapted to the current constructive requirements. The present study demonstrates that the insulated rammed earth cubicle (IRE) under study has a similar thermal response than a conventional construction system insulated with extruded polystyrene (XPS) in summer conditions under free floating and controlled temperature conditions.

As it is well known, rammed earth has important structural limitations and they are aggravated with smaller thicknesses. For this reason, the use of rammed earth as enclosure could be an interesting solution that avoids possible structural limitations, specially, in multi-story buildings.

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References

[1] Transition to Sustainable Buildings. Strategies and Opportunities to 2050. IEA 2013. ISBN: 978-92-64-20241-2

[2] IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[3] Karimpour M, Belusko M, Xing K, Boland J, Bruno F. Impact of climate change on the design of energy efficient residential building envelopes, Energy and Buildings (2015); 87:142–154. DOI: 10.1016/j.enbuild.2014.10.064

[4] Stazi F, Tomassoni E, Bonfigli C, Di Perna C. Energy, comfort and environmental assessment of different building envelope techniques in a Mediterranean climate with a hot dry summer, Applied Energy (2014); 134:176–196. DOI: 10.1016/j.apenergy.2014.08.023

[5] Terés-Zubiaga J, Campos-Celador A, González-Pinoa I, Escudero-Revilla C. Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain, Energy and Buildings (2015); 86:194–202. DOI: 10.1016/j.enbuild.2014.10.018

[6] Fahmy M, Mahdy MM, Nikolopoulou M. Prediction of future energy consumption reduction using GRC envelope optimization for residential buildings in Egypt, Energy and Buildings (2014); 70:186–193. DOI: 10.1016/j.enbuild.2013.11.057

[7] Fang Z, Li N, Li B, Luo G, Huang Y. The effect of building envelope insulation on cooling energy consumption in summer, Energy and Buildings (2014); 77:197–205. DOI: 10.1016/j.enbuild.2014.03.030

[8] Azari R. Integrated energy and environmental life cycle assessment of office building envelopes, Energy and Buildings (2014); 82:156–162. DOI: 10.1016/j.enbuild.2014.06.041

[9] Friedman C, Becker N, Erell E. Energy retrofit of residential building envelopes in Israel: A cost benefit analysis, Energy (2014); 77:183-193. DOI: 10.1016/j.energy.2014.06.019

[10] Samani P, Mendes A, Leal V, Guedes JM, Correia N. A sustainability assessment of advanced materials for novel housing solutions. Building and Environment (2015); 92:182-191. DOI: 10.1016/j.buildenv.2015.04.012

[11] Reddy BVV, Jagadish KS. Embodied energy of common and alternative building materials and technologies. Energy and Buildings (2003); 35:129-137

[12] Reddy BVV. Sustainable materials for low carbon buildings. International Journal of Low-Carbon Technologies (2009); 4:175–81

[13] Melià P, Ruggieri G, Sabbadini S, Dotelli G. Environmental impacts of natural and conventional building materials: a case study on earth plasters, Journal of Cleaner Production (2014); 80:179-186

[14] Kenneth I, Miller A. Thermal behaviour of an earth-sheltered autonomous building–The Brighton Earthship. Renewable Energy (2009); 34(9):2037-2043. DOI: 10.1016/j.renene.2009.02.006

[15] Heathcote K. The thermal performance of earth buildings. Informes de la Construcción (2011), 63(523):117-126. DOI: 10.3989/ic.10.024

[16] Li Q, Sun X, Chen C, Yang X. Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study. Energy and Buildings (2012); 49:317–326

[17] Taylor P, Fuller RJ, Luther MB. Energy use and thermal comfort in a rammed earth office building. Energy and Buildings (2008); 40:793–800

[18] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated, Meteorologische Zeitschrift (2006), 15(3):259-263. DOI: 10.1127/0941-2948/2006/0130

[19] Cabeza LF, Castell A, Medrano M, Martorell I, Perez G, Fernandez I. Experimental study on the performance of insulation materials in Mediterranean construction. Energy and Buildings (2010); 42:630–636. DOI: 10.1016/j.enbuild.2009.10.033

[20] Johansson P, Hagentoft CE, Kalagasidis AS. Retrofitting of a listed brick and wood building using vacuum insulation panels on the exterior of the facade: Measurements and simulations. Energy and Buildings (2014); 73:92–104. DOI: 10.1016/j.enbuild.2014.01.019

[21] Rossi M. Innovative façades lightweight and thin systems with high inertia for the thermal comfort application in office buildings in Southern Europe. Journal of Green Building (2011); 6(2):107-121. DOI: 10.3992/jgb.6.2.107

[22] Dong X, Soebarto V, Griffith M. Design optimization of insulated cavity rammed earth walls forhouses in Australia. Energy and Buildings (2015); 86:852–863

[23] EN ISO 6964:1996. Building components and building elements. Thermal resistance and thermal transmittance. Calculation method

[24] EN ISO 13786:2001. Thermal performance of building components. Dynamic thermal characteristics. Calculation method

[25] de Gracia A, Castell A, Medrano M, Cabeza LF. Dynamic thermal performance of alveolar brick construction system. Energy Conversion and Management (2011); 52:2495–2500. DOI: 10.1016/j.enconman.2011.01.022